National Aeronautics and Space Administration

MCLAURIN Jacobs Space Exploration Group

SPACE LAUNCH SYSTEM

Space Launch System Core Stage Thrust Vector Control Test and Flight Experiences

Aerospace Control and Guidance Systems Committee
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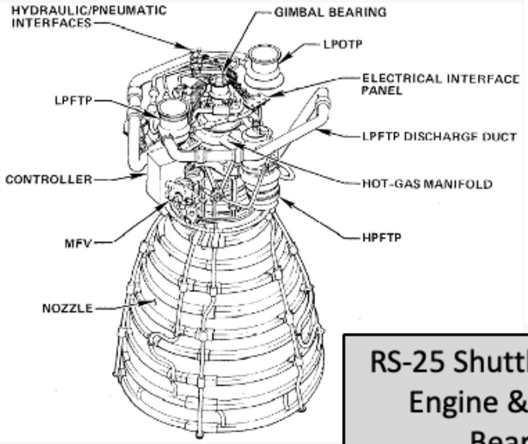
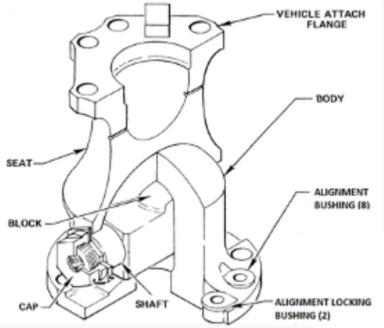
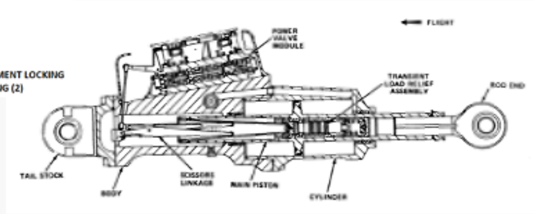
Overview

- SLS Core Stage (CS) is a 27.6 ft x 212 ft stage with over 2.4 Mlbm of structure and propellant
- Thrust Vector Control (TVC) is provided by vectoring 4 RS-25E Core Stage Engines
- 4 (booster) + 8 (core) TVC DoF
- New thrust structure, Shuttle heritage engines & actuators
- SLS team pursued extensive TVC modeling & test leading to findings and confident flight rationale
- Fully successful first flight Nov 16, 2022





RS-25 Shuttle Heritage Engine & Gimbal Bearing



Shuttle Heritage Mech Feedback Actuators

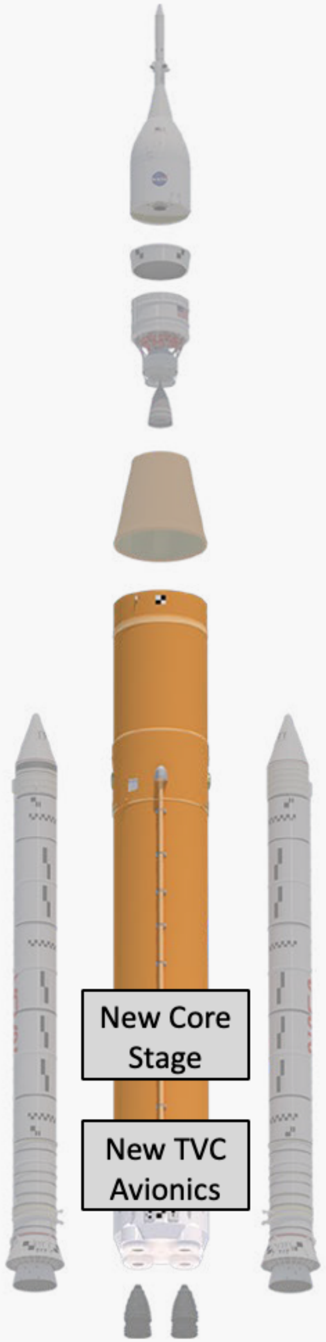


Image: NASA / SLS Ref. Guide

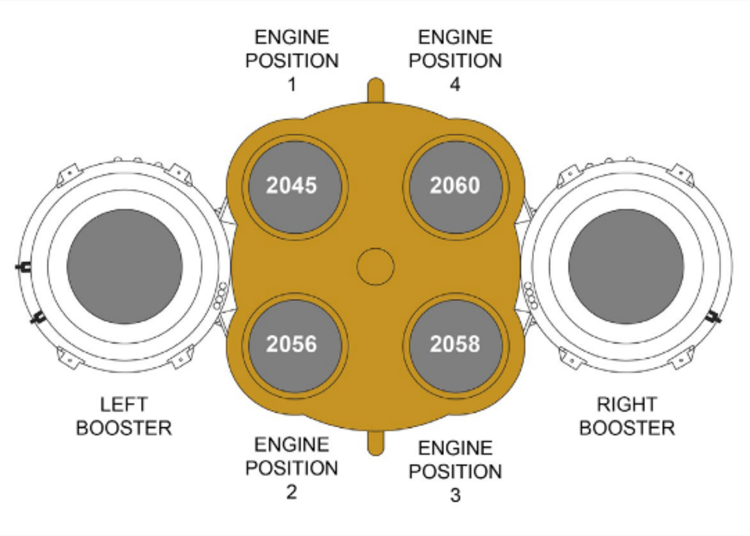


Image: NASA / SLS Ref. Guide

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Test & Modeling Environments Relevant to Core Stage TVC

Actuator & Controller Testing

2-axis Inertial Load Simulator TVC Lab

Engine test stand

Heritage Shuttle

Full TVC testing

Ambient TVC test

Green Run Hot Fire TVC test

Artemis 1 Flight

Structure testing

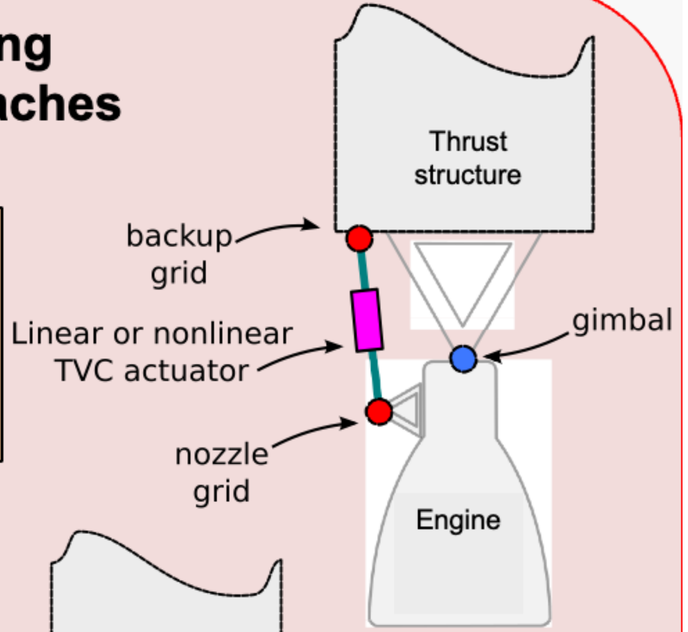
Core stage modal test

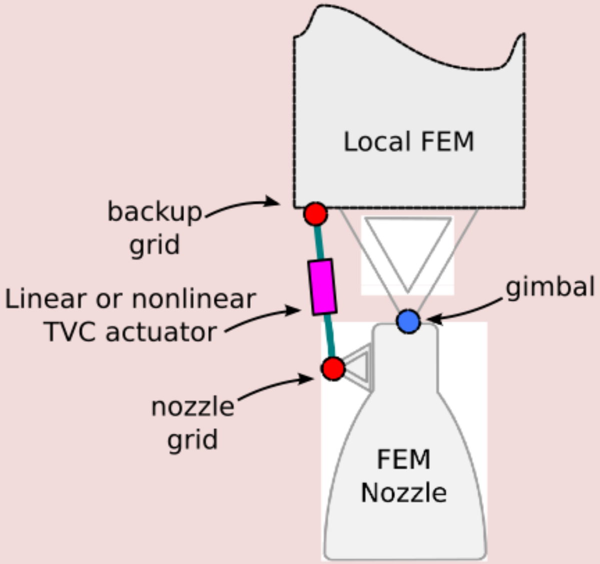
Engine modal test

A complementary set of test environments and conditions allowed the actuators and structure to be investigated separately and together.

Modeling Approaches

Simplex TVC: Lumped Stiffness & Minimum DOF



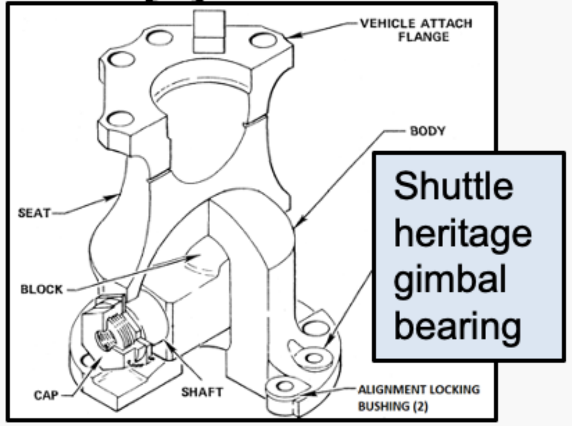


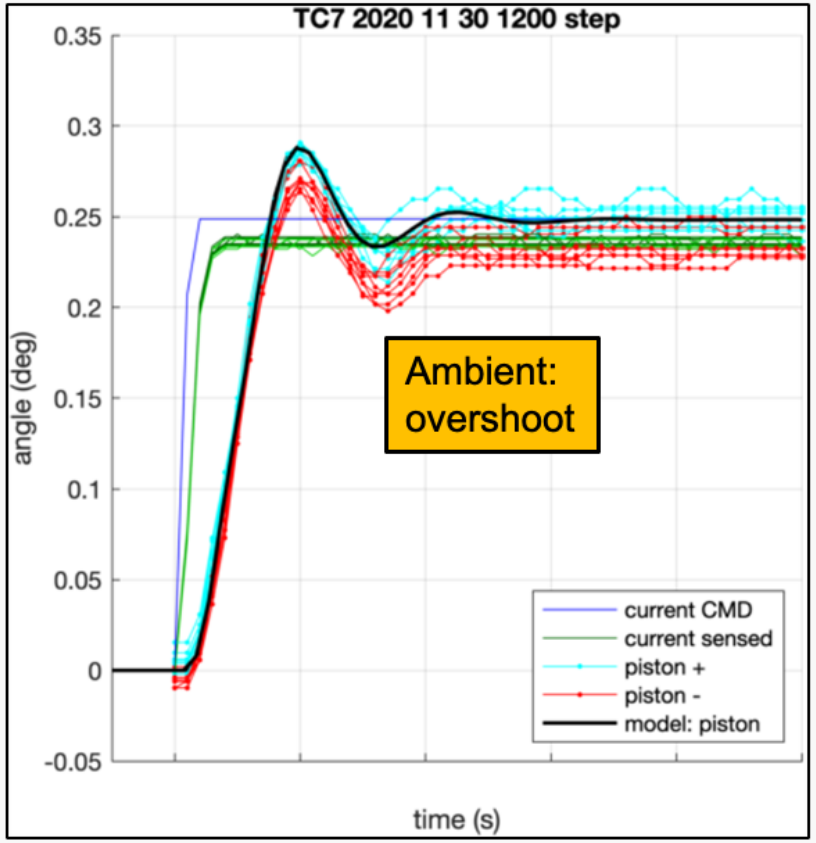
MASV: Coupled TVC-FEM

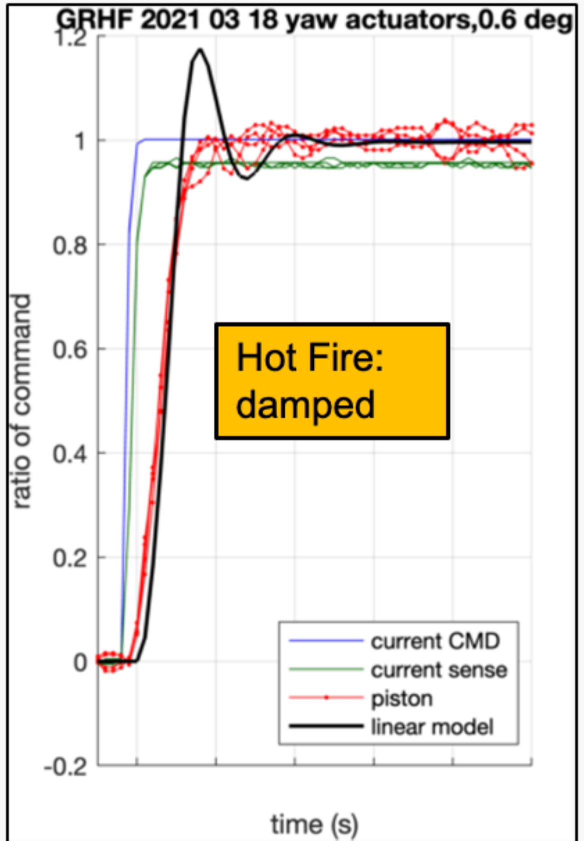
Advances in friction, structural, and gimbal modeling required to replicate test data

TVC Model Updates after Green Run Testing: Friction

- **Effects of gimbal Friction clearly observed during SLS hot fire [1]**
- **Shuttle observed friction in Main Propulsion Test Article (MPTA) hot fire vectoring, but a Limit Cycle Oscillation (LCO) never appeared in flight [8]**
  - Simple models of gimbal friction appear in historical models
- **Prior to Green Run SLS models never included gimbal friction**
  - Longstanding assumption that it could be neglected
- **After Green Run, friction models included using multiple approaches [2]**
  - Simple: Keene & Jeff Brouwer implementations
  - Dahl & LuGre
  - Modified LuGre



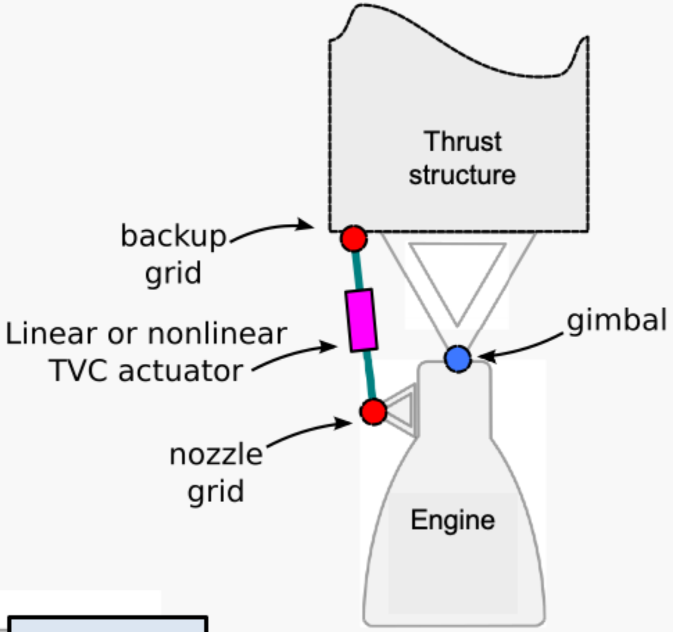




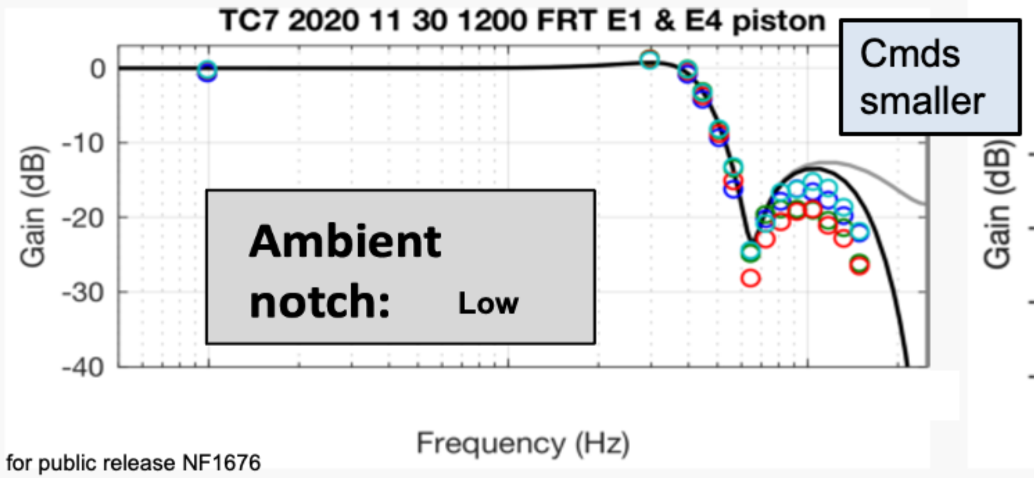
TVC Model Updates after Green Run: Stiffness

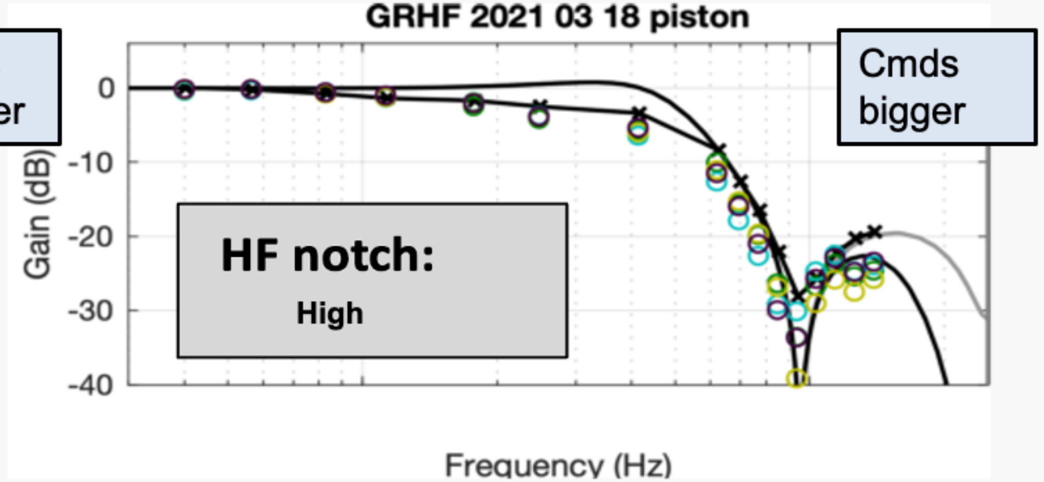
- **Green Run ambient & Hot Fire showed different load resonance frequency**
  - Observed via notch in command to piston frequency response
- **Simplex Model lumps all stiffness outside the actuator control loop into a load stiffness, K_L**
  - $K_L \rightarrow$ all compliances in path: engine, gimbal, clevises, thrust structure
- **KL can be determined from load resonance frequency, ω_L**
  - Moment arm, R, Engine Inertia, Jn are known and duct stiffnesses, Kn negligible
- **Bounding analysis for flight rationale assumes the softer structure**
  - Conservative prediction of LCO
- **Cause for change in stiffness eventually determined**
  - Nonlinearities associated with loaded gimbal and small amplitude actuator behavior

$$\omega_L = \sqrt{\frac{K_L R^2 + K_n}{J_n}}$$



Load resonance derived from actuator command to piston notch frequency





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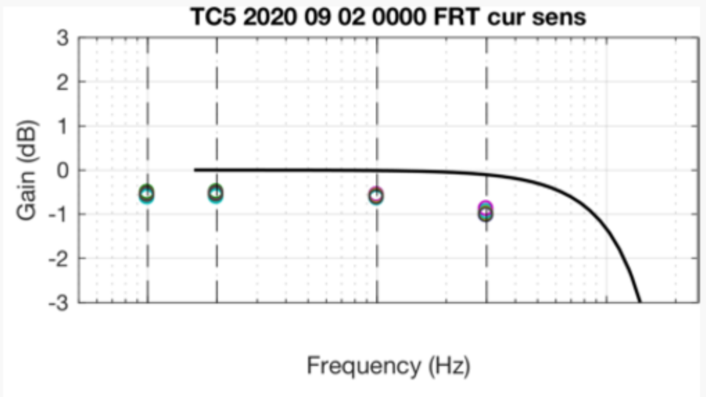
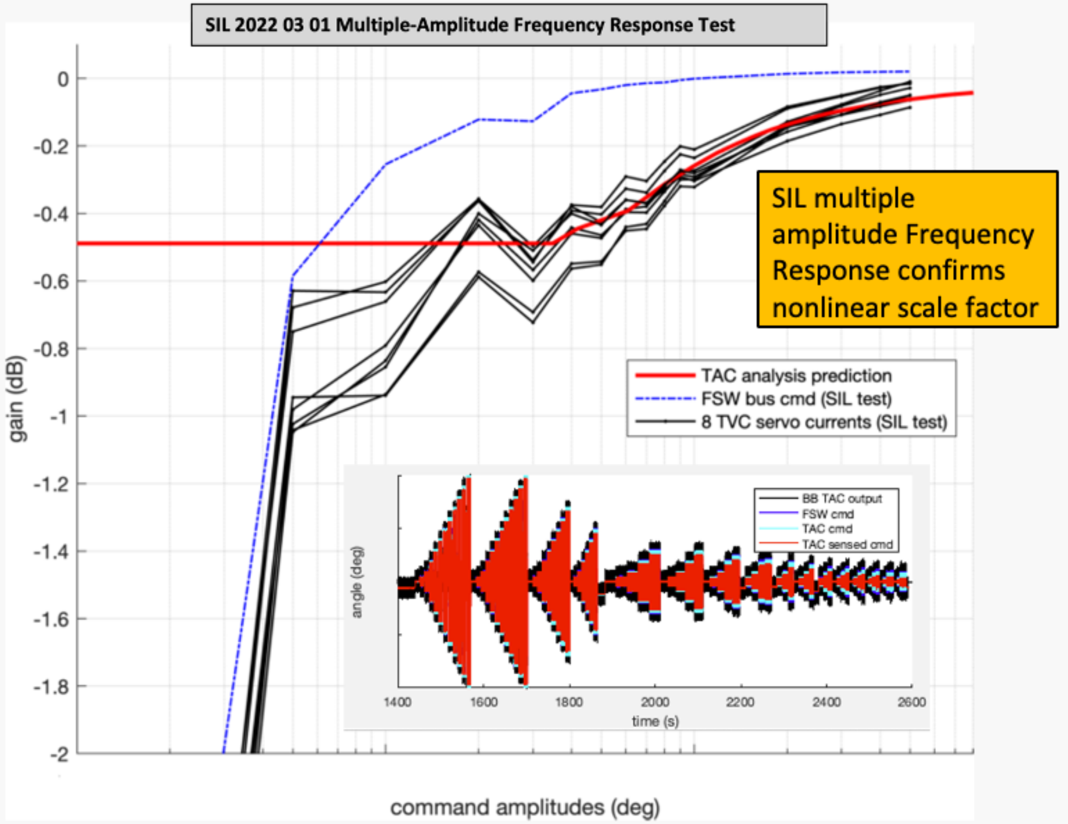
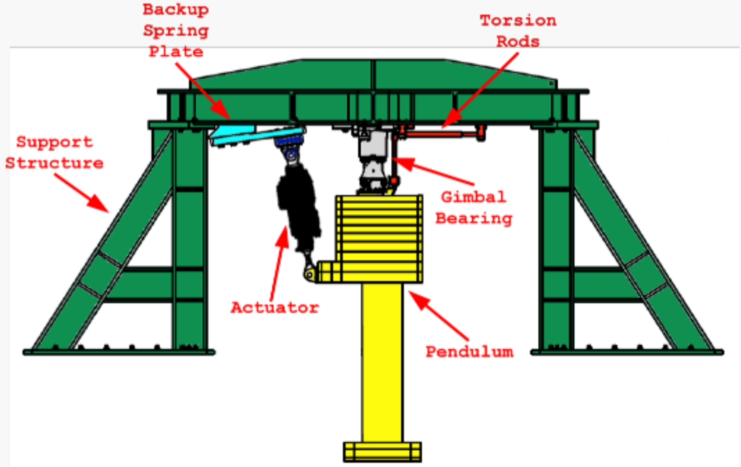
TVC Model Updates after Green Run: Avionics Command Path Gain

- **SLS TVC Actuator Controller (TAC) commands Core Stage TVC**
  - New digital component designed to mimic Shuttle's analog box, Shuttle Ascent Thrust Vector Controller (ATVC)
- **MSFC 2-axis Inertial Load Simulator (ILS) & Green Run testing showed DC offset**
- **Actuator vendor confirmed presence of scale factor nonlinearity in commanded current**
  - due to crossover distortion in servo-amplifier design
- **Hardware in the Loop Systems Integration Lab (SIL) Frequency Response Testing confirmed behavior**
  - Also discovered FSW truncation operation in command quantization that can yield similar gain decrease

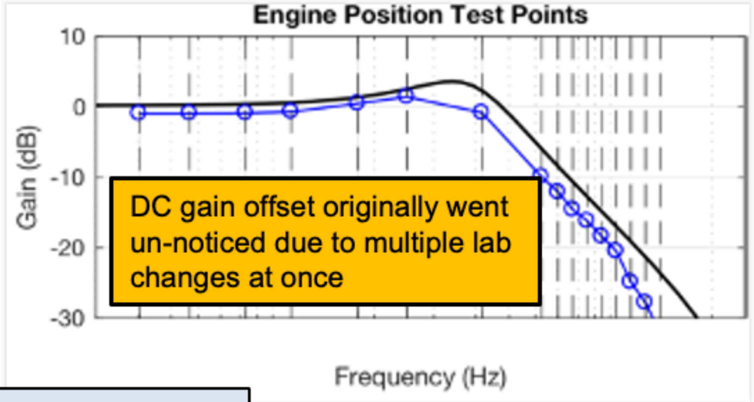
Command to servo current shows DC offset during Ambient GR Testing





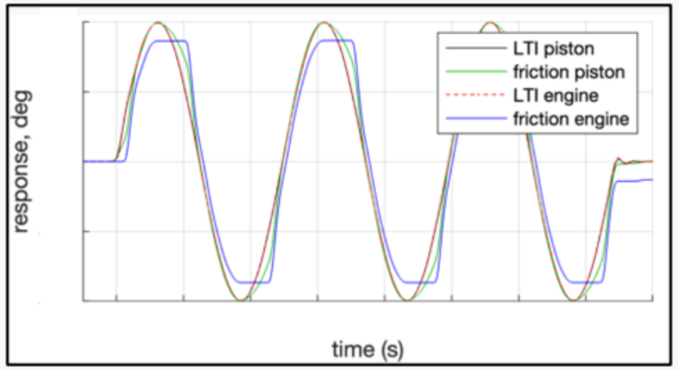


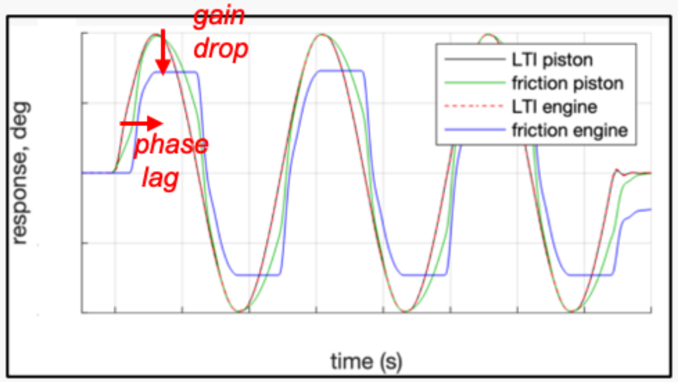
MSFC 2-axis Inertial Load Simulator Facility



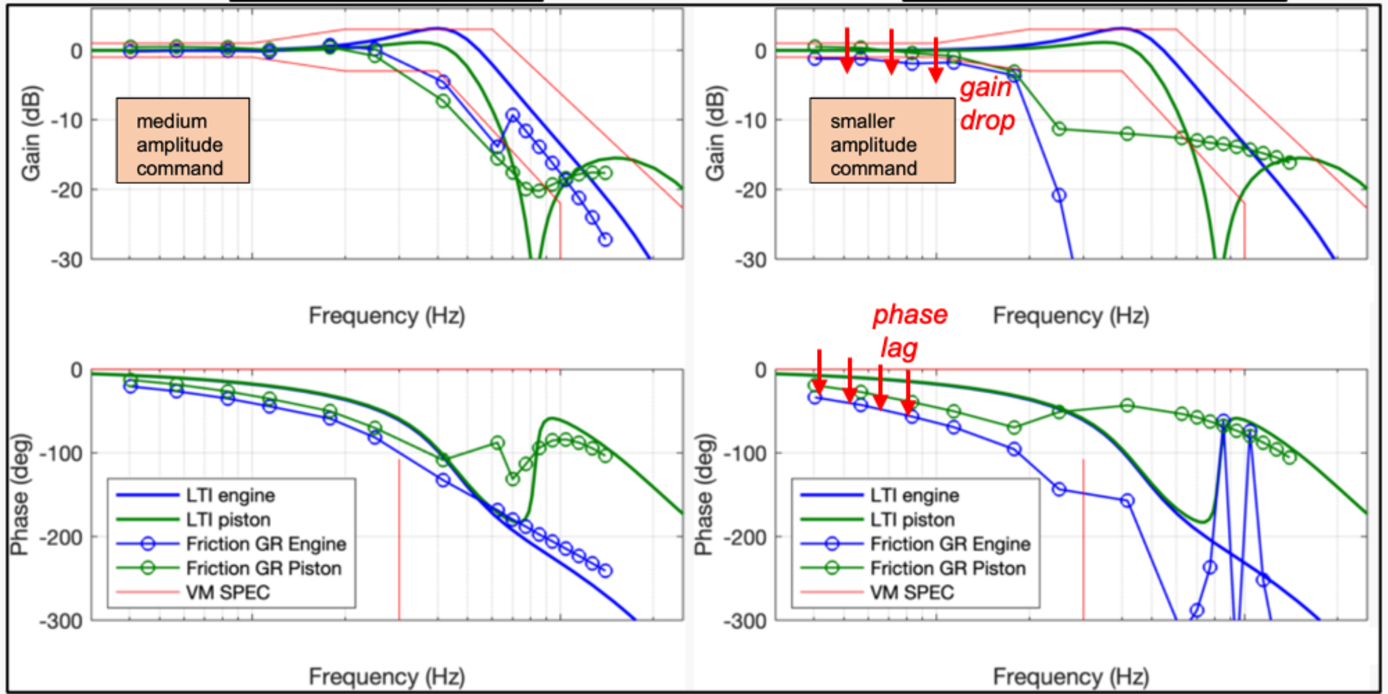
Gimbal Friction Degrades TVC Response, Produces Flight Control LCO

- **Gimbal friction results in degradation of the TVC piston and engine responses**
- **This nonlinearity can produce a Limit Cycle Oscillation (LCO) in Vehicle Flight Control System Loop**



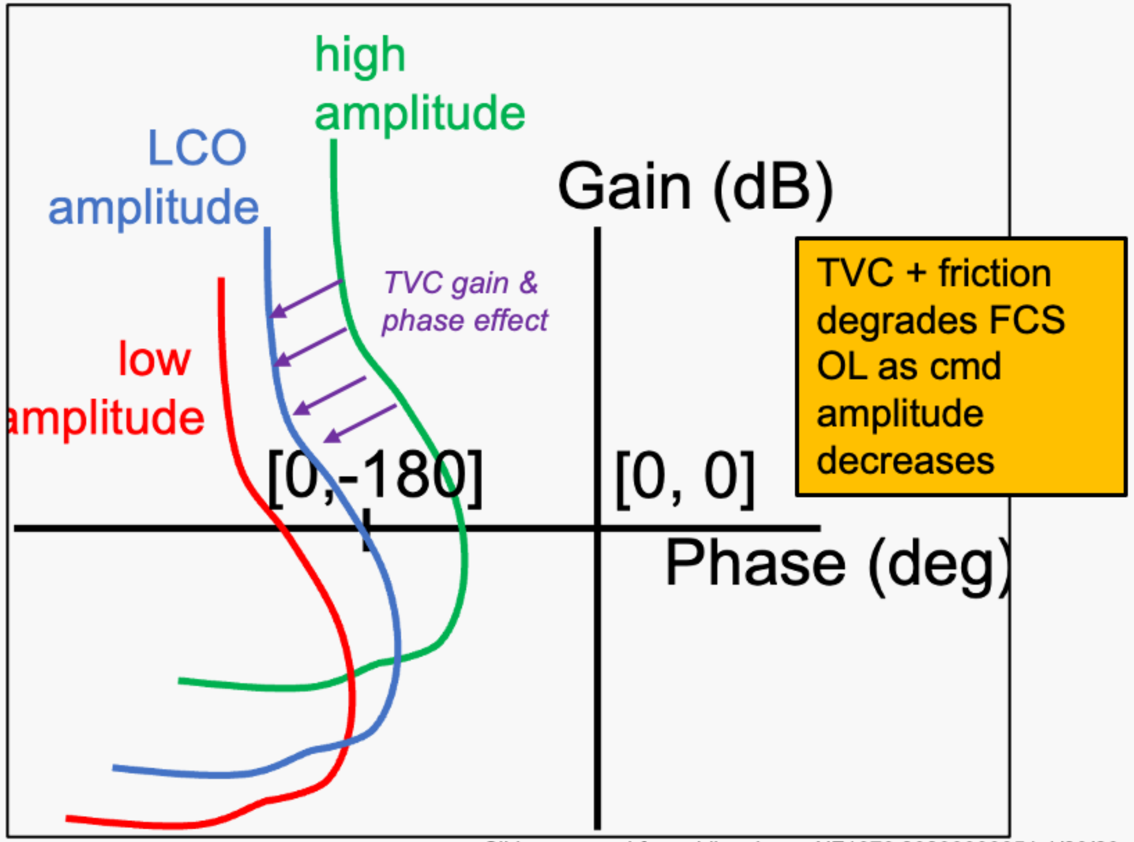


TVC response, medium cmds → *degradation* → TVC response, half of medium cmds



- **Amplitude at which TVC gain & phase causes FCS open loop (OL) to reach [0dB,-180deg] will indicate LCO amplitude**

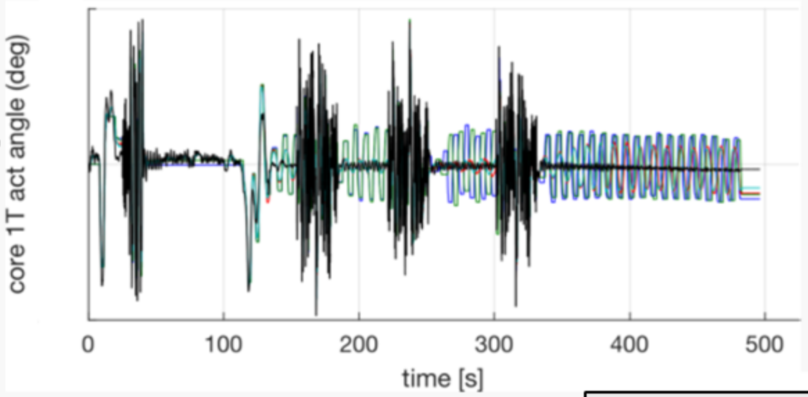
FCS Nichols OL: TVC Friction Effect

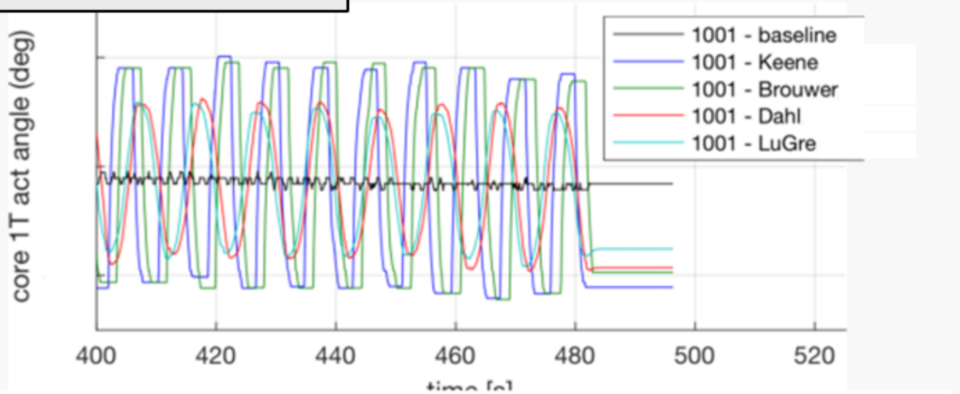


Bounding LCO Predictions for Artemis I Flight Rationale

- **TVC Step and Frequency Response departures accepted for for Artemis I**
  - Artemis I flight rationale based on acceptability of LCO prediction
- **Simplex model adjustments bound the solution**
  - Variety of friction models: Simple (Keene/Brouwer), Dahl, LuGre, tuned based on Green Run & Shuttle MPTA
  - Utilized Range of stiffnesses observed during Green Run testing
  - Included the -1dB TAC command gain effect

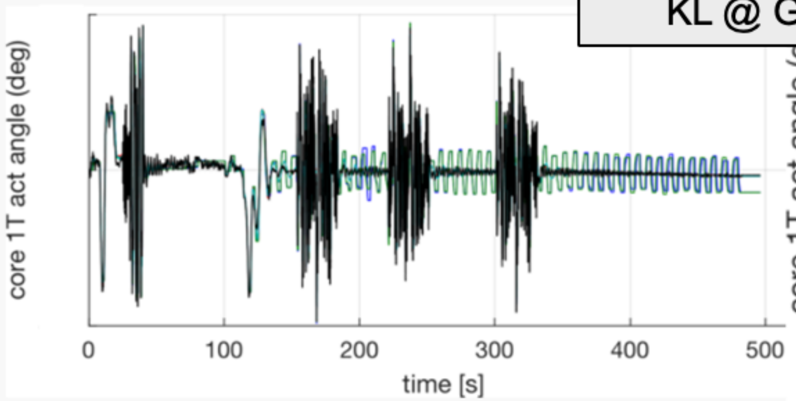
KL @ ambient lower value

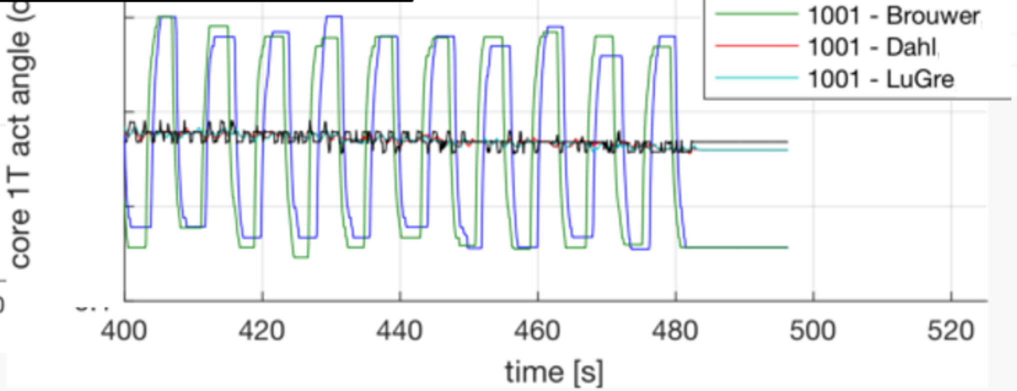




- **Time domain analysis shows LCO at small amplitude, near FCS crossover frequency**
  - Core flight only, boost flight shares authority with Solid Rocket Booster (SRB) TVC
- **Not additive with Programmed Test Input periods (PTIs)**
  - Amplitude of PTI larger than LCO amplitude
- **Higher load stiffness reduces propensity for LCO**

KL @ GRHF higher value





LCO content in core stage flight found to be acceptable: small amplitude, low frequency, and only present during quiescent periods

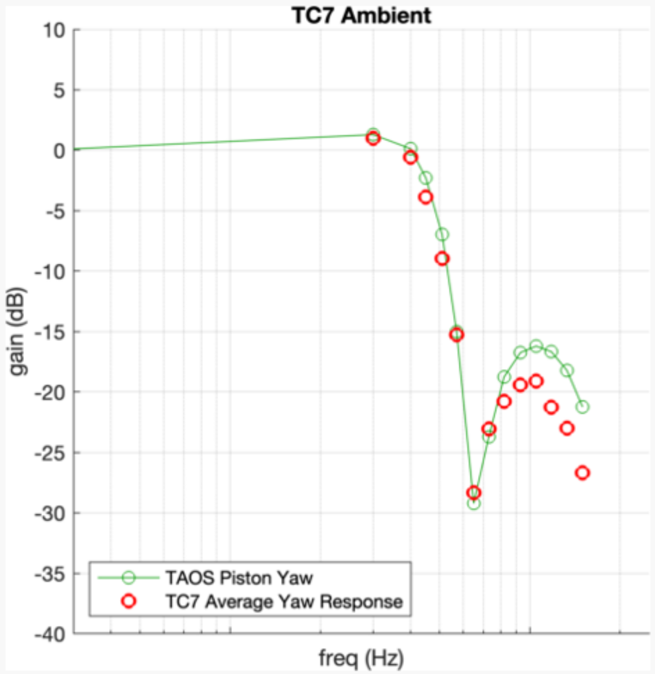
Developments after Acceptance of Flight Rationale

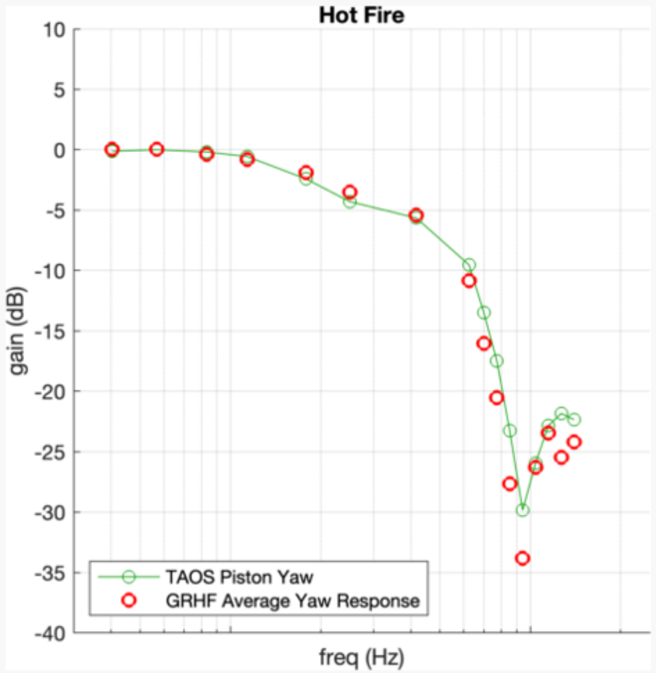
- **Acceptability of flight control stability analysis and predictions of Bounding LCO → Artemis I Flight Rationale**
- **Following development of flight rationale, a cross-disciplinary team was formed with loads & dynamics, TVC, and flight control engineers along with core stage & engine contractors**
  - To improve friction modeling
  - To explain difference in stiffness between hot fire and ambient
  - To determine acceptability of and/or mitigations for Core Stage TVC on future SLS vehicles

<u>Advances in Understanding:</u>

- **Flight expected to have higher stiffness as was observed in Green Run**
  - Gimbal stiffness under loaded conditions
  - Small loads and command amplitudes during ambient shows
- **TAOS (Two Actuator Operational Simulation)**
  - Flex body effects of the gimbal required modeling each half as a separate stiffness in addition to the typical single-spring load stiffness
  - Vector model of gimbal joint and friction torques
  - Advanced model of friction developed “modified LuGre” that best fit Green Run
- **TAOS fidelity with Green Run Hot Fire anchored suggested no LCO would be present in flight**

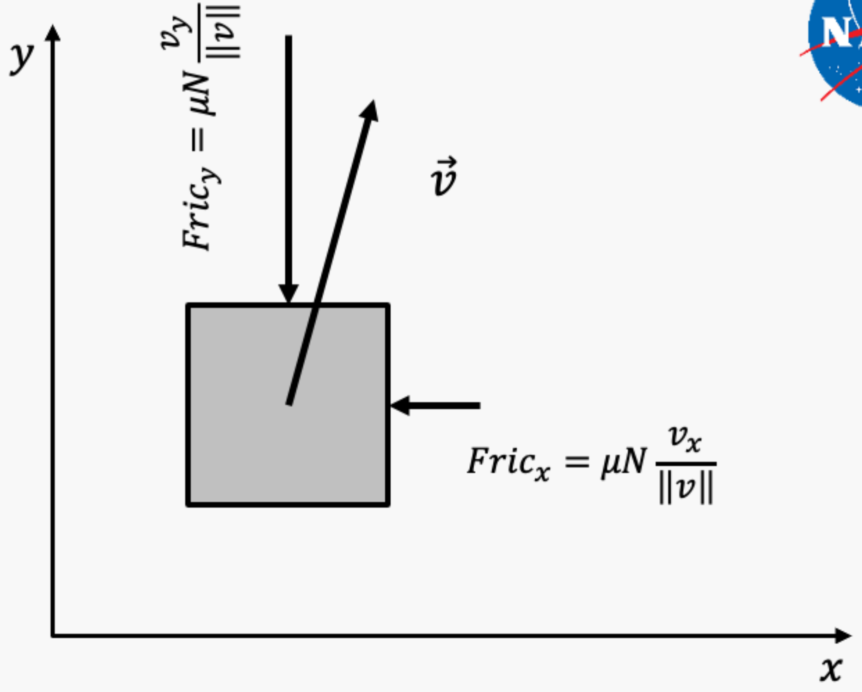
TAOS Modeling Advances Required to Represent Green Run Ambient & Hot Fire Test Responses

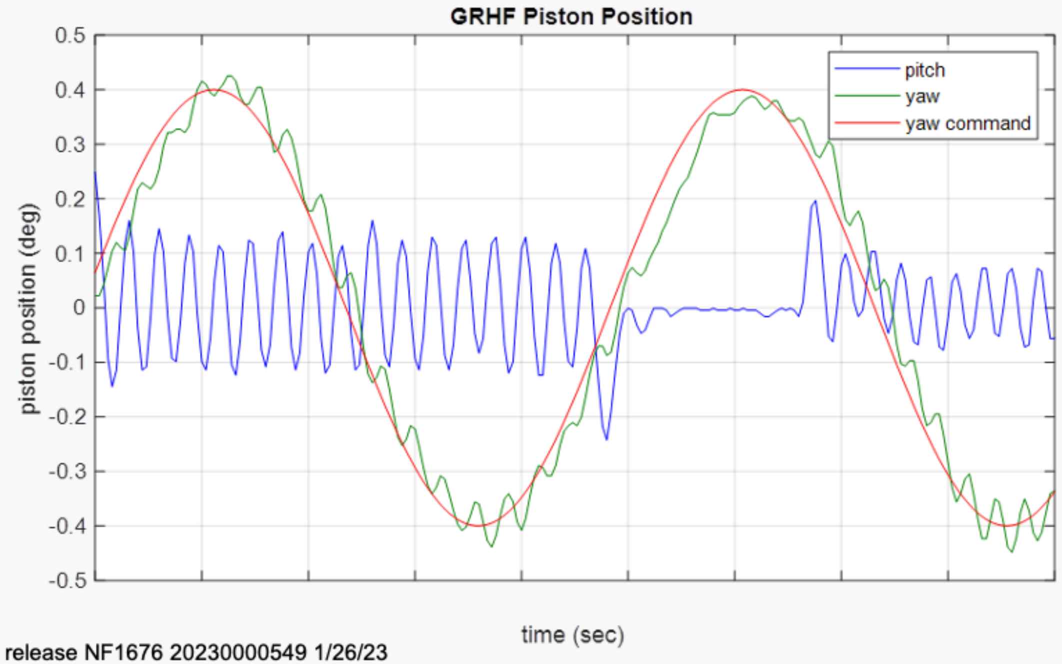


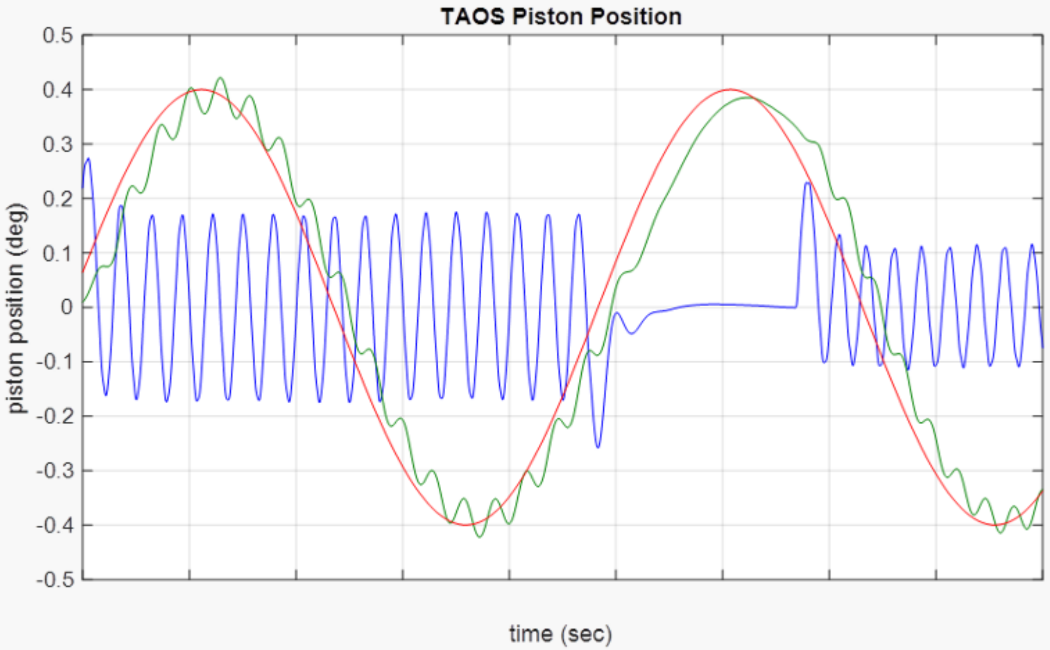


Additional Modeling – Multi-Axis Modeling

- **Multi axis behavior captured with TAOS model**
  - Each axis modeled at the same time and had effects on each other
  - Agreed well with GRHF cross axis behavior
- **Friction models now acted in multiple DoF**
  - Allowed for proper friction maximum and projection (friction vector effect)
  - Measurable friction reduction present in model and data due to this effect



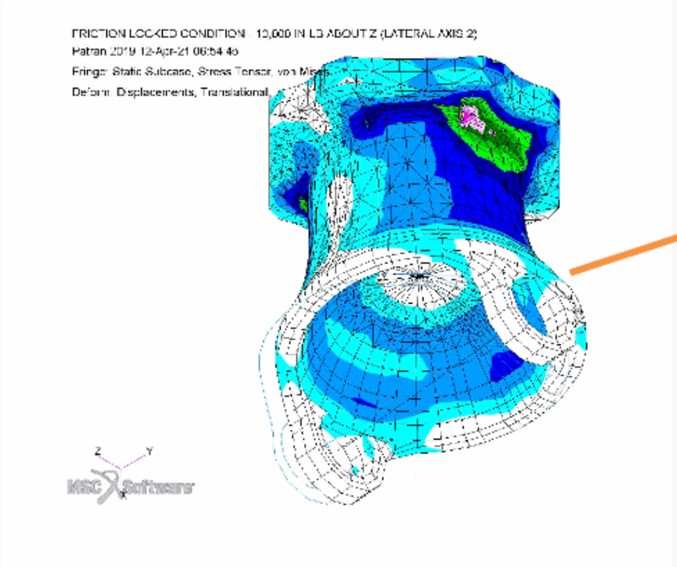


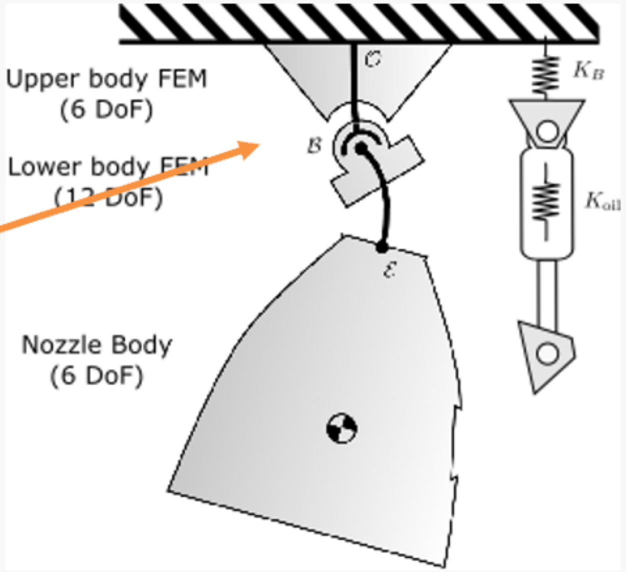


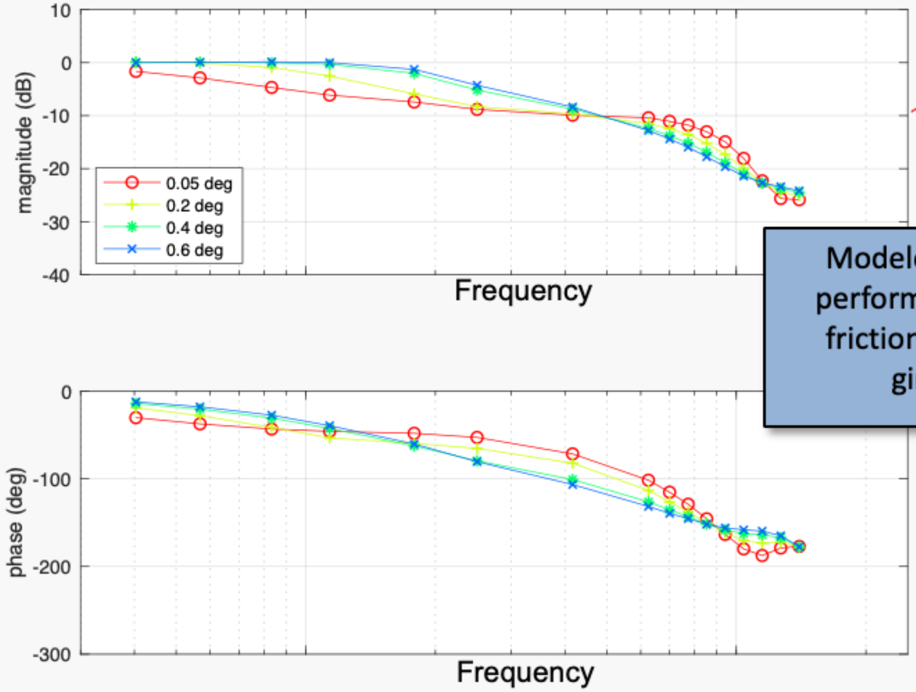
Gimbal Rotational Dynamics Coupled by friction

- **Gimbal structural compliance now modeled via finite element model (FEM) derived stiffness matrices**
  - DoFs added for top/bottom gimbal: beam models
- **Friction torque couples rotational DOF of gimbal structure**

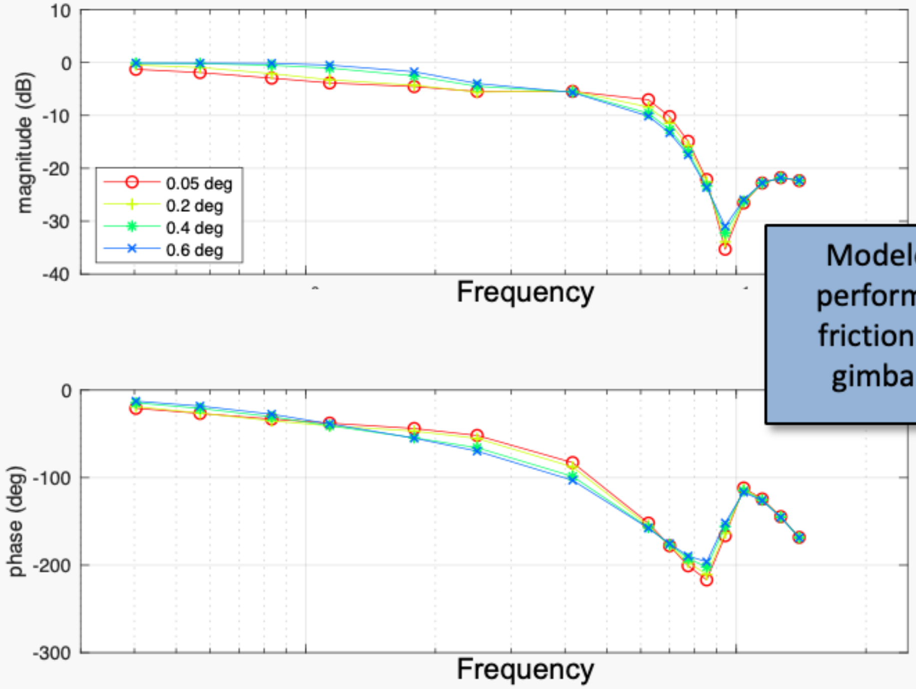
- **Additional Gimbal DOF Fidelity required to fully represent system with all observed response features**
  - amplitude dependence frequency response
  - piston response notch depth and
  - Character of step response transients & offset







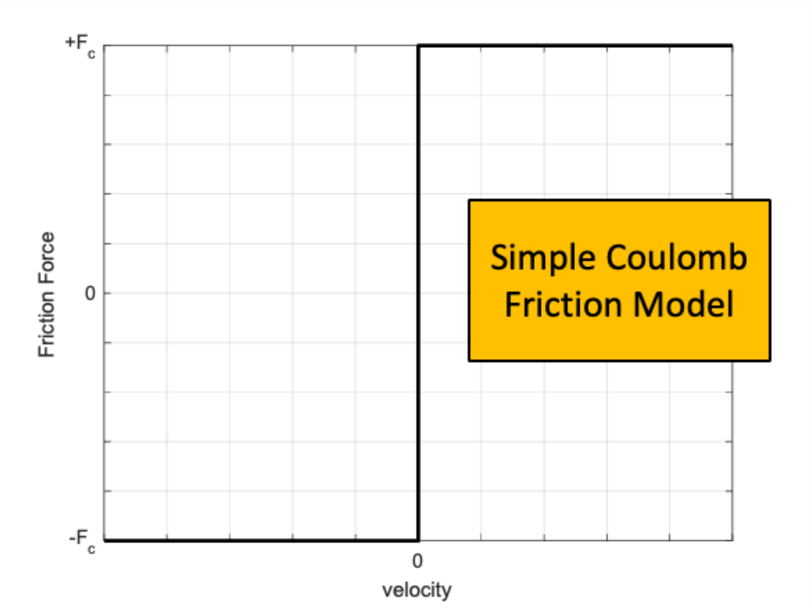
Modeled CS TVC performance with friction and rigid gimbal

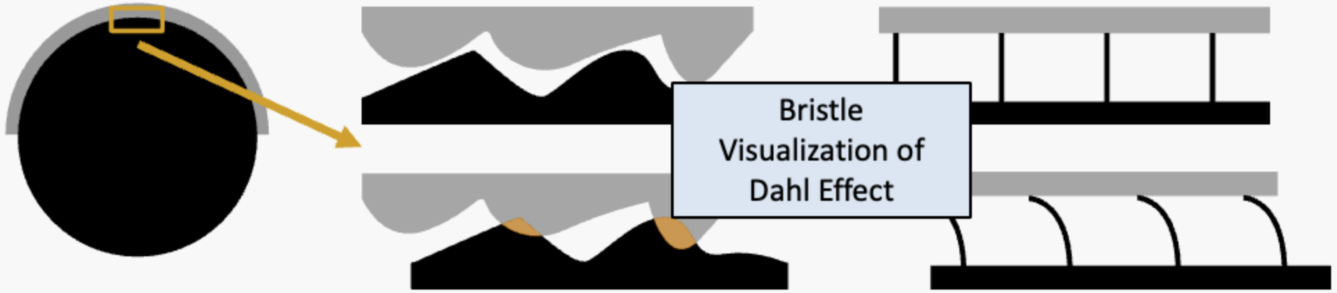


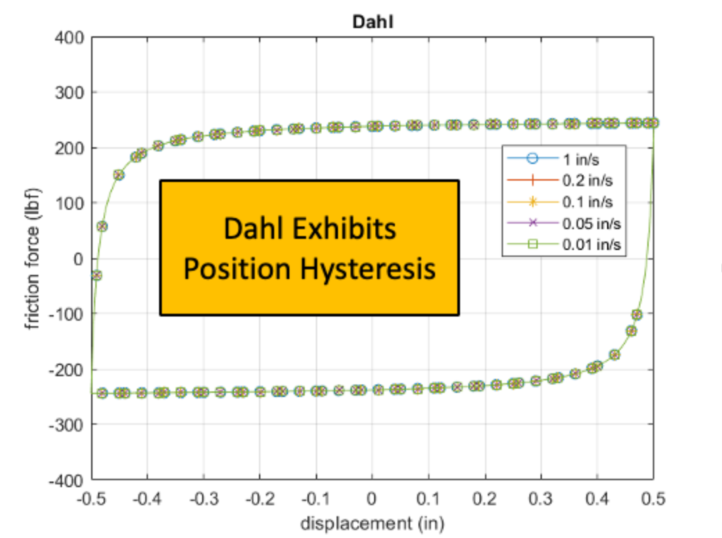
Modeled CS TVC performance with friction and 6DOF gimbal stiffness

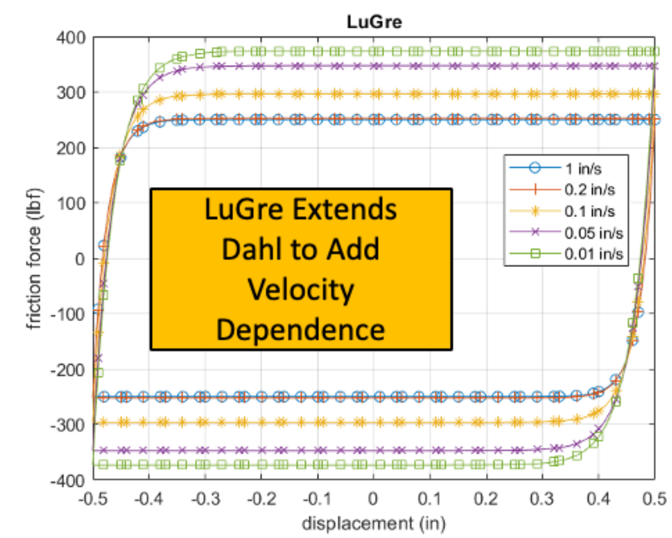
Advanced Friction Modeling Required to Represent Observed TVC Response

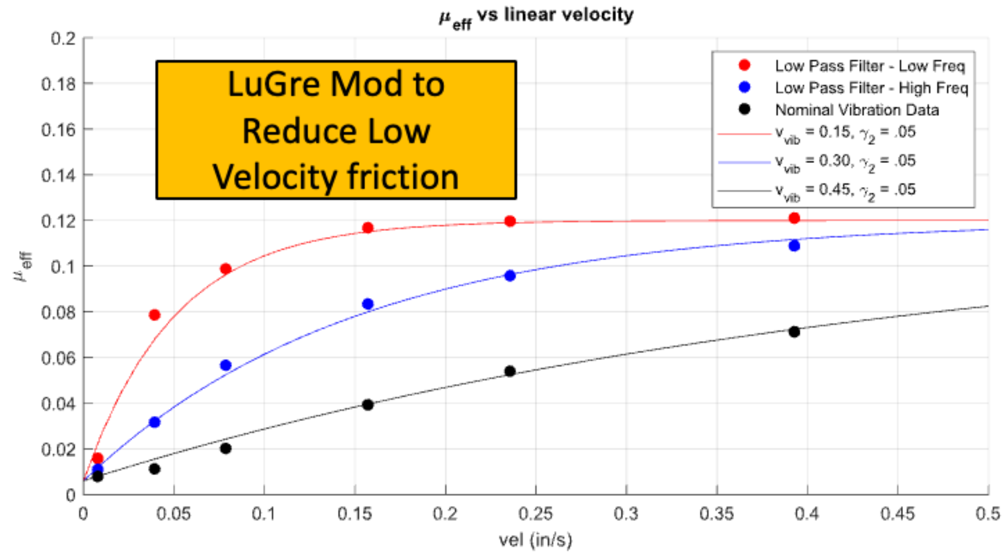
- Simple Coulomb friction was not sufficient to represent observed behavior
- Dahl position dependent effect was evident
- LuGre velocity dependence needed, but not in present form
- Modification to LuGre model implemented to lower friction response at low velocity due to vibrational environment





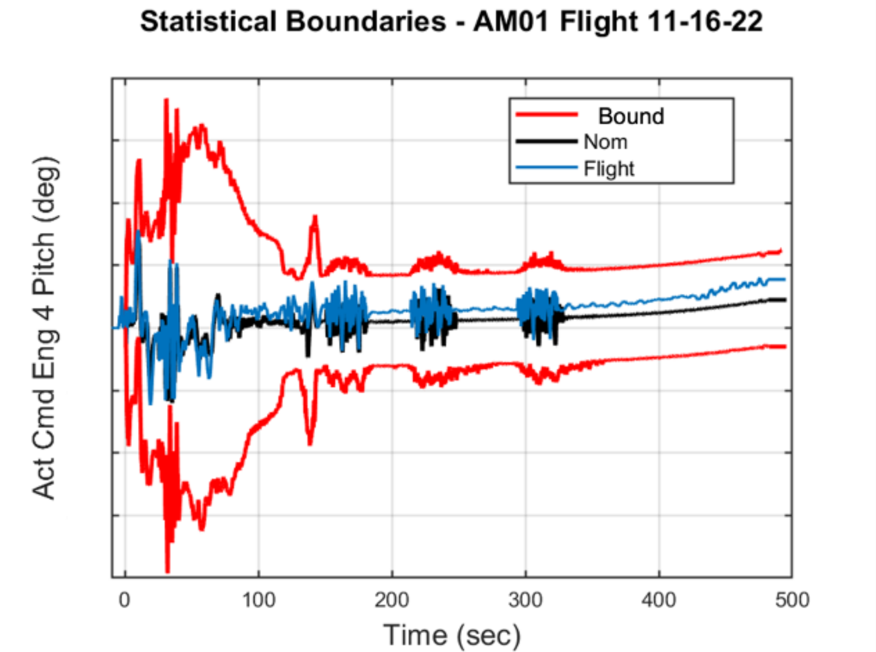


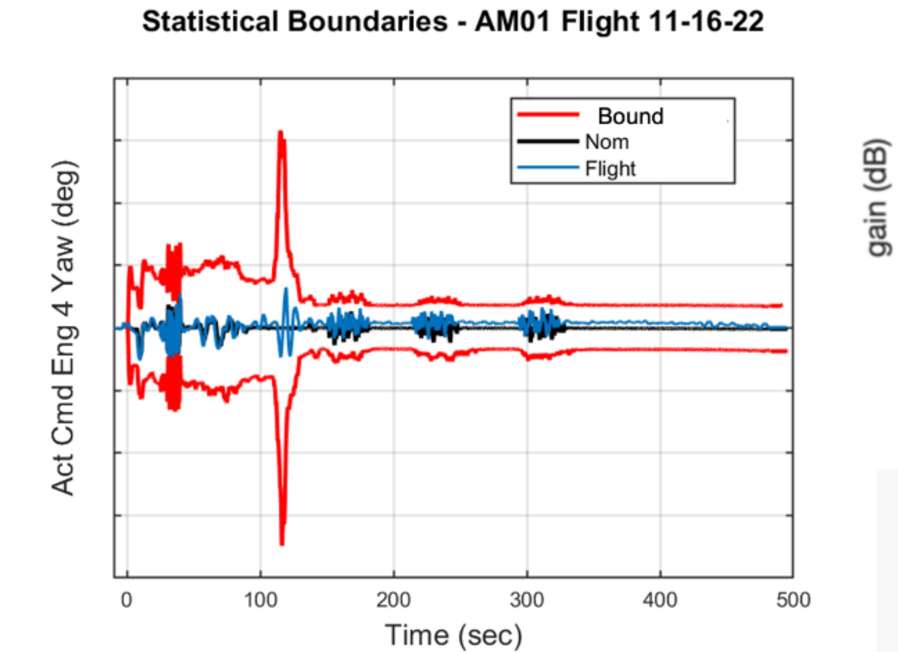


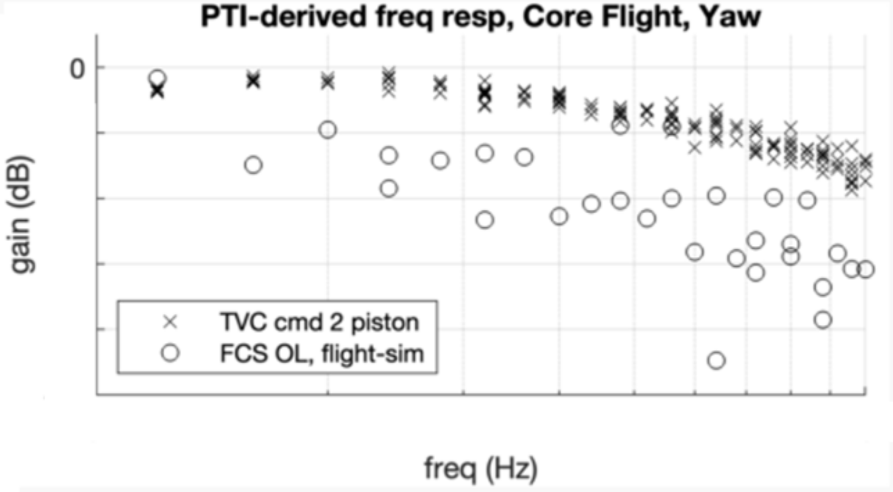


Artemis 1 Flight Response

- **Artemis I flight on Nov 16, 2022: FCS was close to nominal predictions**
- **Some small TVC amplitude oscillation present**
  - Not as clearly persistent as pre-flight LCO predictions but within bounding pre-flight predictions
- **Program Test Inputs (PTI) response of FCS open loop show evidence of decreased gain effect that could be considered consistent with modeled gimbal friction effects**
  - Friction has worse effect on engine than piston → engine necessarily shows up in PTI FCS OL
  - Green Run Hot fire could not determine absolute gain of engine response
- **Post Flight Prelim Evaluation: gimbal friction appears larger than at Green Run, but still a small amplitude effect**
  - Green run simultaneous high and low frequency commanding produces dither
  - Higher acoustically-induced vibratory environments at Green Run lowers friction
  - Exoatmospheric Flight thrust larger than sea level Green Run Hot fire test







Concluding Remarks

- Green Run testing was essential to uncover critical knowledge about the response of Core Stage TVC System in various conditions
- Test anchored models confidently certified FCS for first flight Artemis I
- First flight of SLS provided confirmation of Green Run findings showing responses consistent with small amplitude LCO caused by gimbal friction
- In-flight PTI excitations reveal key information about the SLS response

- This foundation of data and experience will help reduce cost, minimize risk, and maximize mission capability as NASA shapes the SLS generation of heavy-lift launch vehicles.

c/o NASA fb

BACKUP

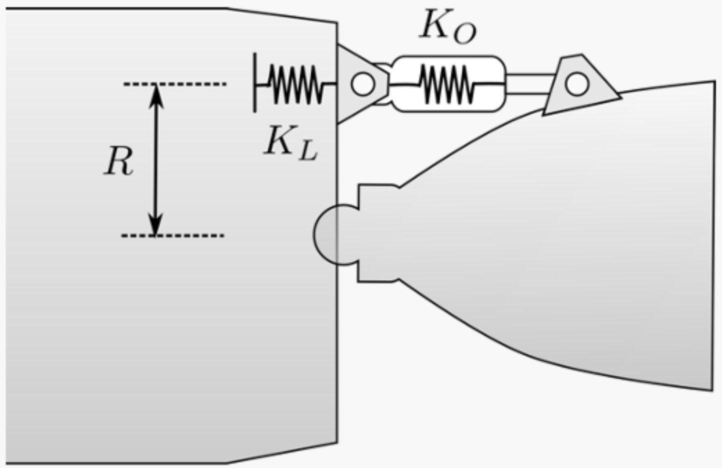
References

- **American Astronautical Society (AAS) GN&C Feb 2023 Conference Session Dedicated to SLS Core Stage TVC Test and Flight Experiences**

  - Orr, et al., "*Advanced Modeling of Control-Structure Interaction in Thrust Vector Control Systems*," AAS 23-153.
  - Russell, C., et al., "*Gimbal Bearing Friction in the SLS Core Stage Thrust Vector Control System*," AAS 23-155.
  - Wall, J., et al., "*Design, Instrumentation, and Data Analysis for the SLS Core Stage Green Run Test Series*," AAS 23-156.
  - Moore, R., et al., "*Structural Dynamics Observations in Space Launch System Green Run Hot Fire Testing*," AAS 23-157.
  - Wall, J., et al., "*Flight Performance and Stability of Space Launch System Core Stage Thrust Vector Control*," AAS 23-158.
  - Stuart, B., et al., "Overview of the SLS Core Stage Thrust Vector Control System Design," AAS 23-152
  - Stuart, B., et al., "Core Stage TVC Systems Engineering Challenges in Reusing Heritage Hardware," AAS 23-154

Importance of the Load Resonance

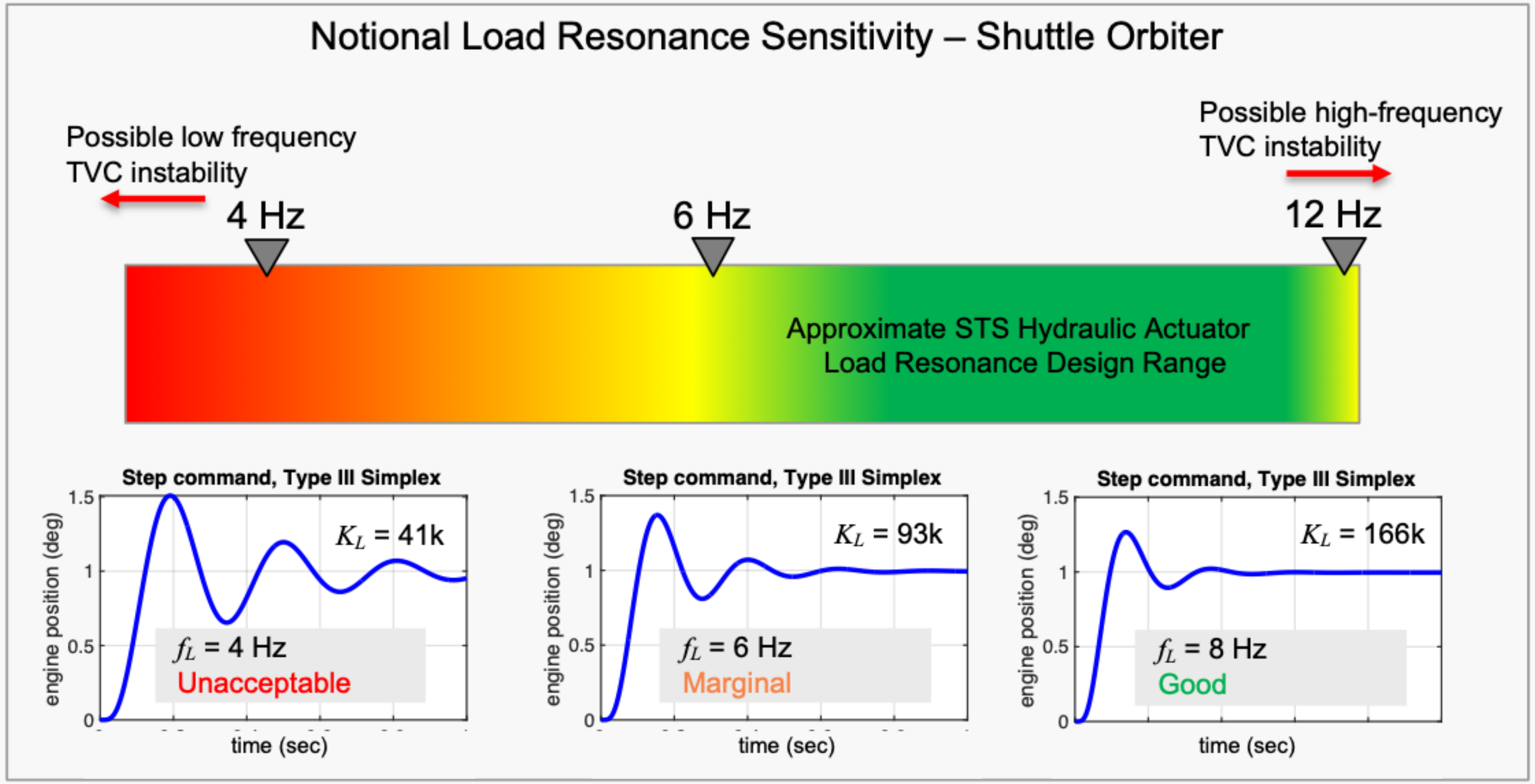
- <u>Open-loop</u> load dynamics with engine feedlines, gravity loading and damping



$$J_n \ddot{\beta} = \underbrace{K_T R x_i}_{\text{Actuator torque}} - \underbrace{C_n \dot{\beta}}_{\text{Damping}} - \underbrace{\left(K_n + K_T R^2\right)}_{\text{Pendulum mode stiffness}} \beta$$

Total Stiffness

$$K_T = \left(\underbrace{\frac{1}{K_L}}_{\text{Load}} + \underbrace{\frac{1}{K_o}}_{\text{Oil}} \right)^{-1}$$



Pendulum Mode (Open Loop)

$$\omega_p \approx \sqrt{\frac{K_T R^2 + K_n}{J_n}}$$

Includes Oil Compliance (not observable)

Load Resonance (Closed Loop)

$$\omega_L \approx \sqrt{\frac{K_L R^2 + K_n}{J_n}}$$

<u>Observable In Test</u> (Notch Frequency)

Linear Simplex Model

- Open-loop load dynamics with rigid engine:

$$J_n\ddot{\beta} = \underbrace{K_T R x_i}_{\text{Actuator torque}} - \underbrace{C_n\dot{\beta}}_{\text{Damping}} - \underbrace{\left(K_n + K_T R^2\right)\beta}_{\text{Pendulum mode stiffness}}$$